Comparative Analysis of Performance of Antilock Braking System using PID and Fuzzy controllers

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Abstract

The Antilock Braking System (ABS) is a crucial safety feature in modern vehicles which prevents wheel lock-up during braking and maintains steerability. The non-linear behavior of different road conditions makes it difficult to predict the optimal brake forces to be applied to minimize the stopping distance and maintain steerability. Control techniques play a crucial role in the optimization of the performance of ABS. This study explores various control strategies, including Bang-Bang, Proportional – Integral – Derivative (PID), and Fuzzy Logic controllers, to enhance the effectiveness of ABS by developing a mathematical and MATLAB/Simulink model of the components. The parameters to be controlled are optimal slip and brake pedal force based on the input parameters which are slip, road condition, coefficient of friction and wheel acceleration. Results indicate that the Fuzzy controlled ABS causes the vehicle stop after about 12.9 sec which is 24.11 % faster than vehicle without ABS and 7.8% faster than vehicle with Bang-Bang controller. The PID controlled ABS causes the vehicle stop after about 12.7 sec which is 25.29 % faster than vehicle without ABS and 9.2% faster than vehicle with Bang-Bang controller and 1.5 % faster than Fuzzy controller. While Bang-Bang control offers simplicity, it lacks precision and efficiency compared to PID and Fuzzy Logic approaches. However, the PID controller demonstrates superior performance, striking a balance between stability and responsiveness. Overall, the PID and Fuzzy controllers exhibit notable advancements in ABS control, ensuring safer braking and enhanced vehicle steerability.

Keywords: Antilock Braking System (ABS), braking distance, Fuzzy Logic Control, PID, Vehicle stability

1. Introduction

The ability to provide for the reduction of its speed quickly and in a stable manner is one of the vital functions of a motor vehicle. A large proportion of situations threatening the safety of a moving vehicle occur while the driver tries to decelerate or stop the vehicle in a situation involving one or more of the following:

a) braking on slippery surfaces
b) braking and cornering (or steering to avoid an obstacle)
c) braking on a surface with asymmetric friction coefficients.

The motivation for an anti-lock braking system (ABS) is that it can provide improvements in the performance of the vehicle under braking compared to a conventional brake system (Aparow et al., 2013; Sanchez-Torres et al., 2012). An ABS controls the slip of each wheel to prevent it from locking such that a high friction is achieved and steerability is maintained(Shah et al., 2020).

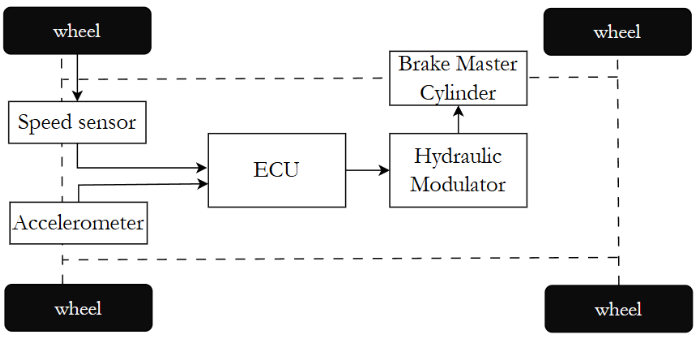


Fig. 1: Antilock Braking System in a vehicle

The Anti-lock Braking System (ABS) plays an important role in automotive safety, which helps the drivers to retain the control of their vehicle during the critical braking operation(Bera et al., 2011; Khachane & Shrivastav, 2016). It achieves this by preventing the wheel lock up and maintaining the vehicle steerability, specifically under the challenging conditions such as braking on slippery surfaces, cornering while braking, or while encountering asymmetric road friction as shown in Fig. 1 (Aly et al., 2011). There have been long presenting challenges prevailing in the effective control of wheel slip due to complexity of tyre-road interaction, non-linear dynamics of braking process, and inherent uncertainties in the system. Due to these uncertainties there is degradation in the performance of conventional controllers which makes robust control methods a key area of focus in ABS system (Tang et al., 2013).

Traditionally, ABS control systems have relied on Bang-Bang controller system due to its simplicity and quick response. However, while handling the non-linearities and model uncertainties, Bang-Bang controller system is not much effective, resulting in suboptimal performance under varying road conditions (Vazquez et al., 2010). In order to manage dynamic systems through feedback control Proportional-Integral-Derivative (PID) controllers have been employed (Mirzaeinejad & Mirzaei, 2010). A Proportional, Integral, and Derivative (PID) uses control loop feedback in control systems applications. The controller first computes a value of error as the difference between a measured process variable and a preferred set point(Yang et al., 2023). It then tries to minimize the error by increasing or decreasing the control inputs or outputs in the process so that the process variable moves closer to the set point. The PID algorithm is given as

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) \tag{1}$$

where y is the measured process variable, r the reference variable, u is the control signal and e is the control error

Fuzzy Logic Controllers (FLCs) has also emerged as more adaptive and flexible solution. FLC uses a set of rules based on human-like reasoning to adjust control forces, making it particularly suitable for managing the unpredictability of road conditions(Labh et al., 2024). As PID controllers relies on mathematical models, unlike it FLCs uses linguistics variables and approximate reasoning to handle complex and non-linear systems(Amirkhani & Molaie, 2023). This makes them useful in situation where there is lots of unpredictability and where it is hard to create precise models. Although FLCs offer clear benefits in managing uncertain and nonlinear conditions, there is still a lack of comprehensive comparative studies between traditional controllers like Bang-Bang and PID, and FLCs within the scope of ABS, as noted in the literature (Aksjonov et al., 2016; Shiza & Kumar Singh, 2023).

To relegate the challenges and implement the need for a robust control strategy in order to manage all the complexities, a thorough examination of various control techniques under various conditions is essential. Using simulation platforms like MATLAB/Simulink helps to model crucial ABS components—such as vehicle dynamics, tire-road interaction, and wheel slip—and test different control strategies to evaluate their effectiveness in optimizing braking force and slip control(Yadav et al., 2019). Using this approach helps for a detailed comparison of how controllers like Bang-Bang, PID, and FLC are used to handle the non-linear behaviors and uncertainties that arises in braking process.

PID and Fuzzy Control techniques perform exceptionally well in nonlinear, complex and even in not mathematically describable systems. This research aims to perform comparative analysis of conventional Bang-Bang controller, PID controller and Fuzzy controller.

2. Methodology

This study presents a comparative analysis of three control techniques—Bang-Bang Controller, Proportional-Integral-Derivative (PID) Controller, and Fuzzy Logic Controller—implemented in an Antilock Braking System (ABS) for passenger vehicles. The primary objective is to assess and compare their effectiveness in minimizing braking distance and regulating wheel slip under varying road conditions. The methodology for the application of control techniques to improve the performance of ABS can be explained by the block diagram in Fig. 2.

The relative slip of the vehicle is fed back to the system to be compared with the optimal slip (0.2) and fed to the controllers as input along with wheel acceleration and wheel speed (depending on the type of controller). The controller, based on the input values, calculates the amplitude of signal to be sent to the brake module to apply required pressure on the hydraulic brake pedal which in turn controls the wheel acceleration and eventually the wheel speed, vehicle speed and slip is calculated.

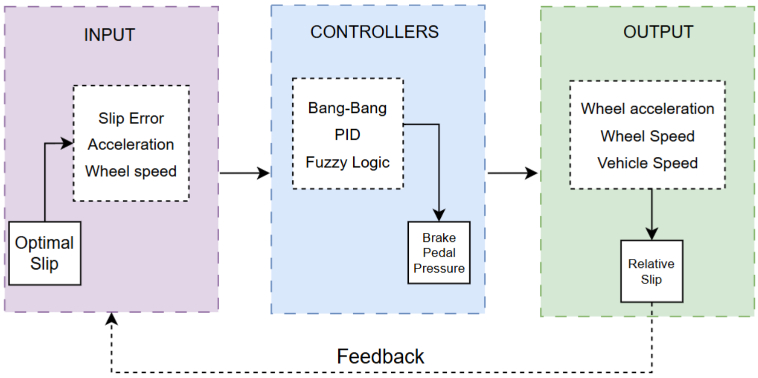


Fig. 2: Control of Anti-Lock Braking system

The Burckhardt tire model is used simulating the longitudinal tire-road interaction. It provides a good balance between modeling accuracy and computational simplicity, making it suitable for real-time control applications. The Burckhardt model describes the friction coefficient (μ) as a nonlinear function of the longitudinal slip ratio (κ):

$$\mu(\kappa) = a_1 \left(1 - e^{-a_2 \kappa}\right) - a_3 \cdot \kappa \tag{2}$$

where,

μ(κ) = Longitudinal friction coefficient

κ = Longitudinal Slip ratio

a_1, a_2, a_3 = Road dependent empirical parameters

If v is the vehicle speed and vw is the wheel speed, the slip ratio κ is calculated as:

$$K = \frac{v - v_w}{v} \tag{3}$$

The longitudinal dynamics of a vehicle during braking describe how the vehicle's speed and wheel rotation change over time due to braking forces. A quarter-vehicle model is used, assuming symmetry and uniform load distribution among the four wheel as shown in Fig. 3.

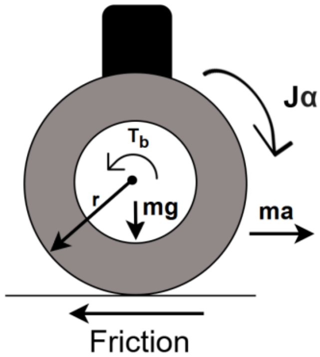


Fig. 3: Vehicle dynamics of the quarter car model

The equation governing the deceleration of the vehicle body due to braking is:

$$m \frac{dv}{dt} = -F_x \tag{4}$$

The rotational dynamics of the wheel are described by:

$$J \frac{d\omega}{dt} = T_b - rF_x \tag{5}$$

where J is the moment of inertia of the wheel, ω is the angular velocity of the wheel, Tb is brake torque applied, r is the effective rolling radius of the tire, m is the mass of the vehicle and Fx is the longitudinal tire force (braking force).

Hydraulic brakes are employed to apply braking force to the wheels. A hydraulic braking system functions by converting the driver's pedal force into hydraulic pressure via a master cylinder, which then actuates brake calipers or drums(Dahal et al., 2023; Mahesh et al., 2024). The resulting friction generates a braking torque that decelerates the wheel. The transfer function for the brake can be written as:

$$G(s) = \frac{K_b}{\tau s+1} \tag{6}$$

Where, K_b is gain factor depending on the system characteristics and τ is the time constant of the actuator.

3. Results and discussion

The performance of ABS system, in terms of braking distance and slip, using 3 different controllers is presented graphically and discussed in this section. The Anti-Lock Braking (ABS) system provides better braking performance in a vehicle. The initial speed of the vehicle was taken 70 m/s. The braking distance and slip of a vehicle without ABS is shown in Fig. 4 and Fig. 5 respectively. The result shows the wheels locking shortly after applying the brakes while the vehicle keeps moving (or skidding) and eventually coming to stop after 17 seconds. Similar results can be seen in the slip curves which reaches to the value of 1 after 6 seconds of braking. The vehicle skids and performs unsatisfactorily in this case.

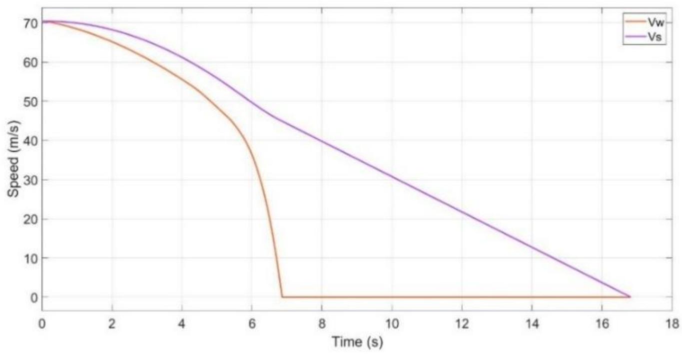


Fig. 4: Braking distance of vehicle without ABS

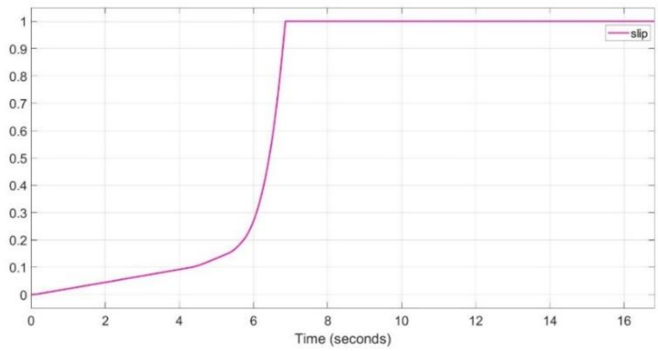


Fig. 5: Slip of vehicle without ABS

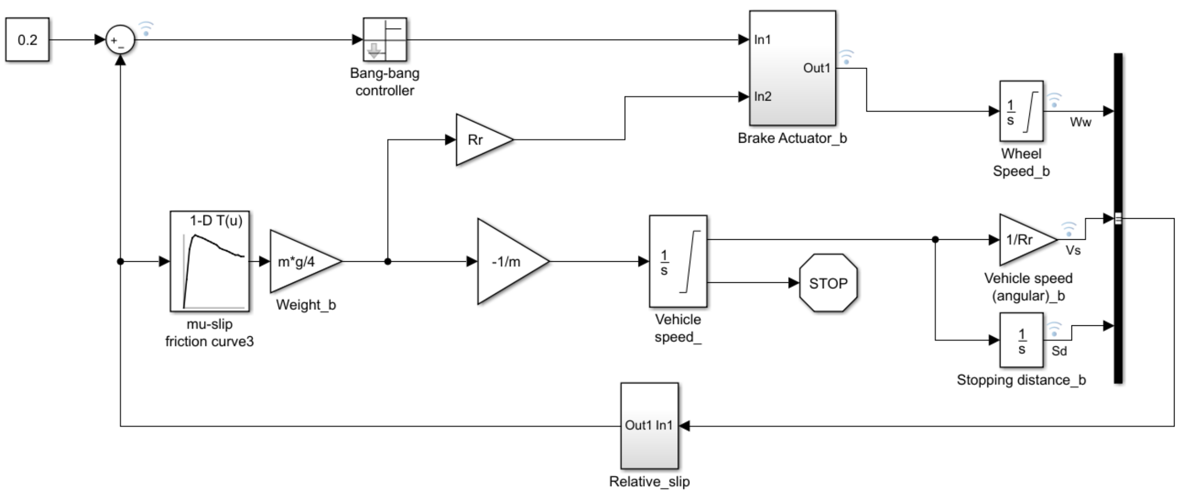
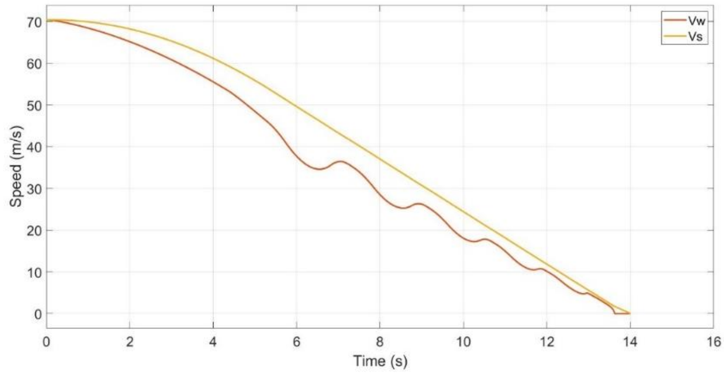
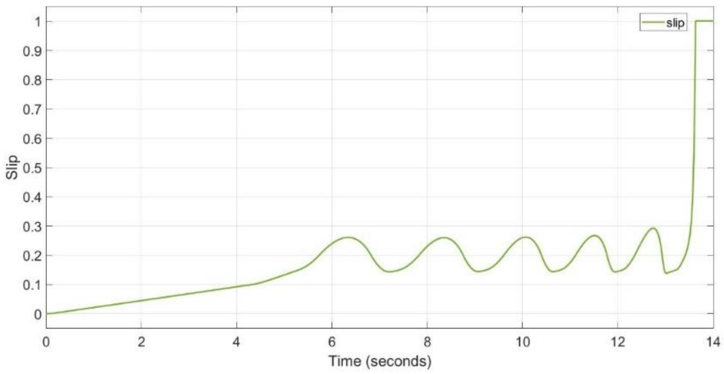


Fig. 6: ABS modeling in MATLAB/Simulink using bang-bang controller

ABS using bang-bang controller, which is the simplest kind of controller, is shown in Fig. 6. The Simulink diagram shows the feedback of slip compared to the optimal slip (0.2) which produces an error signal which is further utilized in the decision making by the controller. The braking distance and slip of the vehicle is shown in Fig. 7 (a) and (b). The Bang-Bang controlled abs causes the vehicle stop after about 14 sec which is 17.6% faster than vehicle without ABS. The slip curve shows the value remains within the range of optimal slip value of 0.2. Bang-Bang controller provides better stopping time and control over the vehicle while braking.



(a)



(b)

Figure 7: (a) Stopping distance of vehicle with ABS [bang-bang controller], (b) Slip variation curve [bang-bang controller]

3.1 ABS with Fuzzy Logic Controller

The Simulink model of ABS with fuzzy logic controller is shown in Fig. 8. The slip error signal along with the wheel acceleration is provided as input to the Fuzzy controller. Mamdani model has been used for the fuzzy controller. Based on the rules set in the fuzzy system, the controller takes the decision to control the hydraulic brake pedal force. The membership function for slip error and wheel acceleration used in fuzzy controller are categorized as NL(Negative Large), NS (Negative Small), Z (Zero), PS (Positive Small) and PL (Positive Large). The output of the Fuzzy controller is determined by the fuzzy rules shown in Table 1, this output controls the application of pressure to the hydraulic brake pedal, it is categorized as QRP [Quick Release in Pressure], SRP [Slow Release in Pressure], H [Hold], SIP [Slow Increase in Pressure], QIP [Quick Increase in Pressure].

Table 1: Fuzzy Rules Set for the controller

SLIP	**WHEEL ACCELERATION**				
	NL	**NS**	**Z**	**PS**	**PL**
NL	QRP	QRP	QRP	QRP	QRP
NS	SRP	SRP	QRP	QRP	QRP
Z	H	SRP	QRP	QRP	QRP
PS	H	H	SRP	SRP	SRP
PL	H	SIP	SIP	QIP	QIP

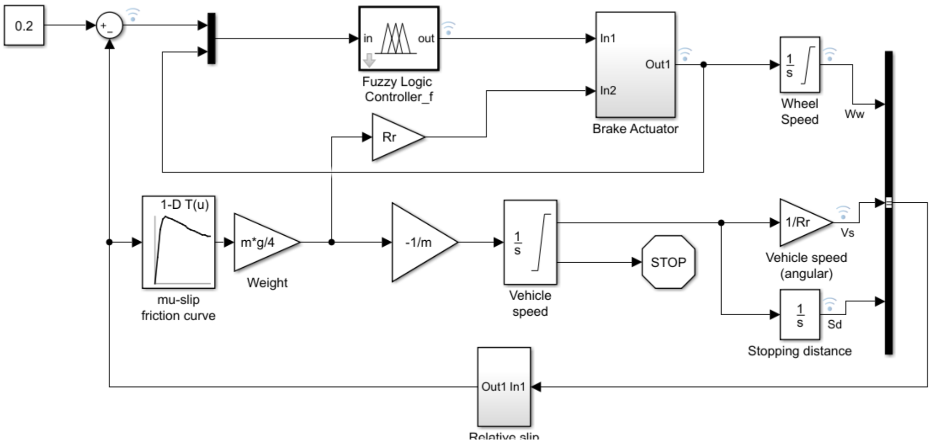
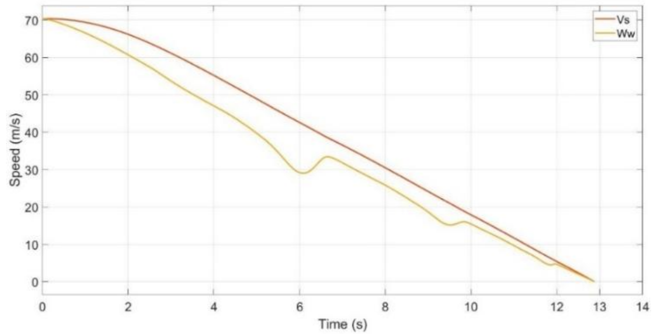
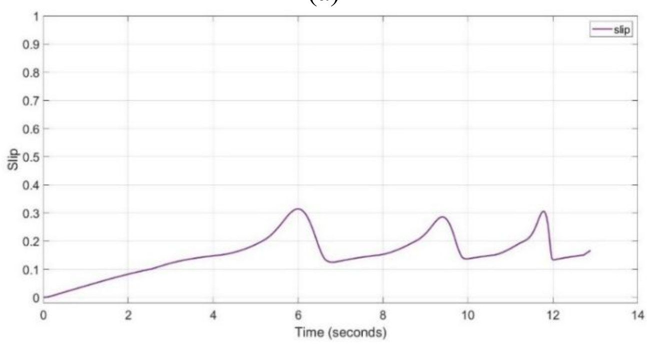


Fig. 8: Simulink block diagram for ABS with Fuzzy Controller

Fig. 9 shows the results for braking distance and slip for the vehicle with ABS controlled by Fuzzy Logic Controller. The Fuzzy controlled ABS causes the vehicle stop after about 12.9 sec which is 24.11 % faster than vehicle without ABS and 7.8% faster than vehicle with Bang-Bang controller. The slip curve shows the value remains within the range (0.1-0.3) of optimal slip value of 0.2. Fuzzy controller provides better stopping time and vehicle control over the Bang-Bang controlled ABS.



(a)



(b)

Fig. 9: (a) Stopping distance of vehicle with ABS [Fuzzy controller], (b) Slip variation curve [Fuzzy controller]

3.2 ABS with PID controller

The Simulink model of ABS with PID controller is shown in Fig. 10. The slip error signal is provided as input to the PID controller. The PID has been tuned using the Simulink tuner. The controller takes decision based on the input error signal and further controls the braking that needs to be done on the vehicle. Fig. 11 shows the braking distance and vehicle slip when the braking is controlled by PID controllers. The PID controlled ABS causes the vehicle stop after about 12.7 sec which is 25.29 % faster than vehicle without ABS and 9.2% faster than vehicle with Bang-Bang controller and 1.5 % faster than Fuzzy controller. The slip curve shows the value remains within the range of optimal slip value of 0.2. PID controller provides better stopping time and vehicle control over the Bang-Bang and fuzzy controlled ABS.

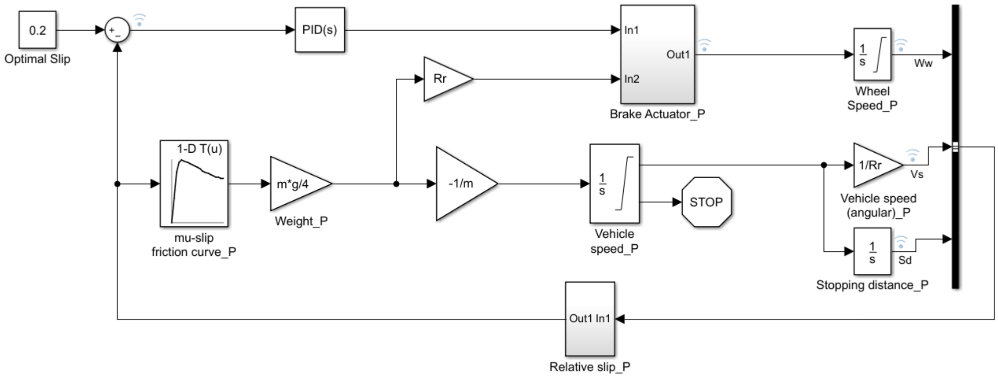
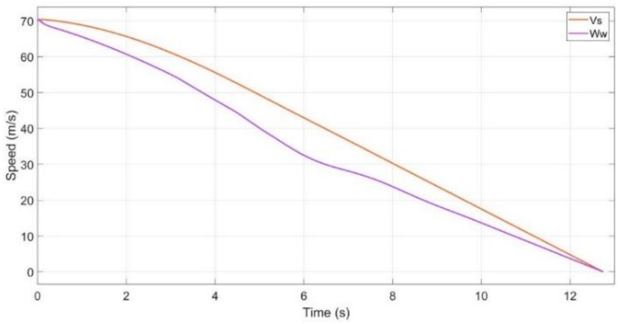
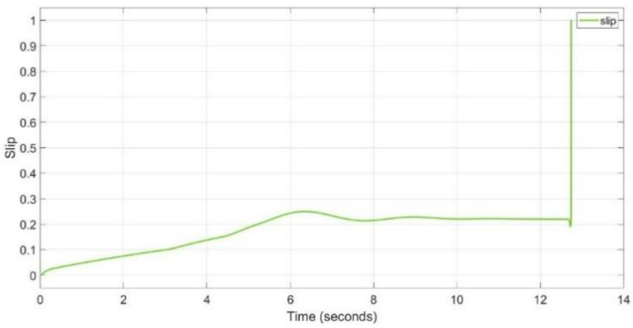


Fig. 10: Simulink model for ABS with PID controllers



(a)



(b)

Fig. 11: a) Stopping distance of vehicle with ABS [PID controller], b) Slip variation curve [PID controller]

4. Conclusion

An Anti-lock Braking System (ABS) model has been developed in MATLAB/Simulink and the simulation results were compared with an ABS system that uses a bang-bang controller, Fuzzy controller and PID controller. Fuzzy controlled ABS causes the vehicle stop after about 12.9 sec which is 24.11 % faster than vehicle without ABS and 7.8% faster than vehicle with Bang-Bang controller. The PID controlled ABS causes the vehicle stop after about 12.7 sec which is 25.29 % faster than vehicle without ABS and 9.2% faster than vehicle with Bang-Bang controller and 1.5 % faster than Fuzzy controller. The use of PID controller provides better results in slip control, steerability and stopping distance of the vehicle in comparison to Bang-Bang controlled and Fuzzy controlled ABS.

This research has its own limitations which provide scopes for future studies in the same field. Following are some recommendations that can be incorporated to widen the scope of this thesis work:

i. The model can be further modified by adding more inputs to the fuzzy controller. Slope of the road can be added as an input parameter while controlling the brake force applied to the vehicle.

ii. The comparisons of ABS model using PID and Fuzzy controller with the ABS models using other controllers such as Fuzzy-PID controller, sliding mode (SM) controller, ANFIS controller etc. can be done and the results with the difference in time for stopping the vehicle can be analysed.
iii. Experimental tests must be performed for validation of the results.

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